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Numerical simulation of storm surge in the submerged radial sandbars of the Southern Yellow Sea, China

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Abstract

Based on the Western Pacific storm surge and astronomical tide simulation system, this paper established simulation model of the features of affected storm surge in this area and give an analysis for the setup of the water level. It shows that there are 3 types of tropical cyclones which can have effects on this area: direct landing, northward after landing and sea northward. For landing north type and offshore activity type, the distribution of setup contours is near parallel to the coastline; for direct landing type, maximum surge obviously occurs at landing point, and setup reduces gradually from the centre to outside.The storm surge in the submerged radial sandbars has a close relation with sea-floor relief and the combination of passing time of typhoon and astronomic tide. It is necessary for storm surge prediction or simulation to consider topography, route and the time going through synthetically.

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Key words: submerged radial sandbars, south yellow sea, storm surge, setup, typhoon path;

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1. Introduction

Storm surge, induced by strong atmospheric perturbations (such as typhoons, tropical cyclones, extratropical cyclones and cold, etc.) is a phenomenon of sea surface abnormal increase or decrease. When the peak storm surge occurs synchronously with the climax of astronomical tide, plus the waves, climb role of the waves and swells, it is prone to make sea water over the levee and lead to inland flood disaster *(Feng Shizuo, 1982).*

Storm surge disasters happen frequently in Jiangsu province. In the Western Pacific, tropical cyclones generated on average of 29 times per year, among which the tropical cyclones affecting Jiangsu Province has an annual average of 3.1 times, and themaximum is 7 times per year*(Ren Meie, 1985)*. On the south-central coast inland shelves of Jiangsu Province, nearly 20,000 square kilometres in the southern Yellow Sea region, it forms a huge radial sand ridge, its wide range, large scale, and complicated hydrodynamic condition is rare in the world *(Chen, 2008)*. On september 14, 1981 a typhoon happens coincide with the lunar tide in early August, which resulted in the sea level rise of more than 2m in the radial sand ridge area, the largest sea level increase in Sheyang river estuary is up to 2.95m, 3.81m in Xiaoyang Kou, and 2.43m in LvSi ocean observation station *(Chen, 1991)*. Yu and Wu*(Yu, 2002; Wu, 2002)* made numerical simulations of five extratropical storm surges in HaiZhou bay in Jiangsu coastal, there is a certain process difference with the observed data, but the biggest set up of water level has a good agreement with the observed value. Zhang Xiang *(Zhang, 2008)* established a mathematical model with high accuracy of Jiangsu coastal storm surge, but the stability is not good and the computing time is very long by using the explicit difference method, and the result of the simulation is not very good. Yu Liangliang *(YU, 2013)* studied the impacts on the radial sand ridge in Jiangsu province by storm surges under the condition of sea-level rise, and simulated several typhoon storm surge which attacked YanCheng by using WRF atmospheric model and Delft 3D. Wang *(Wang, 2014)* simulated storm surge along Jiangsu coast with a Jele wind parameters model.

Located at the inner continental shelf of Jiangsu offshore, the submerged radial sandbars of the Southern Yellow Sea is for about 20 thousand square kilometres. Its wide range and complex hydrodynamic condition are rare in the world. Considering the complex terrain of radial sandbar area and storm surge occurs frequently in Jiangsu coastal area, it is very necessary to make an extensive study for the features of storm surge propagation in this area.

2. Numerical model and verification

This paper established a 2-dimensional astronomical tide-storm surge coupled model, including wind pressure field model, the Pacific Northwest tidal wave model and the model of Jiangsu coastal storm surge. The wind pressure field model adopting Holland *(1980）* parameter model superimposing background wind field, it provides the driving force of the atmosphere for the other two sub-models. The Northwest Pacific Northwest tidal wave model covers the Pacific margin of the East China Sea, South China Sea, Philippine Sea, Sulu Sea and other seas that near Pacific Ocean.

Under the driving of atmospheric force provided by Holland model, the Pacific Northwest tidal wave model gives level tidal and surge water level for the open boundary. Finally, with atmospheric force and open boundary water level, the model of Jiangsu coastal storm surge can simulate the storm surge along Jiangsu coast. The model of Jiangsu coastal storm surge is relatively small, so that a more fine mesh density can be prepared for better characterization of the coastal terrain.

2.1 The wind and pressure models

Holland model *(Holland, 1980)* gives the wind field, this parameter model can give a more accurate wind and pressure field, which contains some of the meteorology parameters depend on empirical or observation to be determine. It is widely used in the risk assessment *(Vickery, 2009).*

The empirical model can better reflect the characteristics of the typhoon gale wind area near the center of the typhoon, but generally limited to the range of several hundred kilometers; because the mobile typhoon affected simultaneously by global weather systems, the wind field generally has large difference with empirical model, it needs to be modified by considering the background wind field. Background wind field uses the second generation of global climate reanalysis database JRA-55 provided by the Japan Meteorological Department. The database contains a total of 55 years of re-analysis of meteorological data from 1958 to 2013, compared with the previous generation JRA-25, the new generation of database has been improved in many places, including highresolution, new radiation pattern, improved four-dimensional variation assimilation methods and the introduction of greenhouse gas effects. The database has 640 grids in the longitude direction and 320 grids in latitude direction, with an accuracy of 0.5625°. The time interval is 6h.

The Synthesis method of background wind field and empirical typhoon model is as follows：

$$V_C = (1 - e)V_M + eV_Q \tag{1}$$

Here V_M is empirical results； V_Q the background； e is a weighting coefficient, to ensure the smooth connection of two wind farm， $e = c^4/(1 + c^4)$， $c = r/(10 \times R)$。

Typhon 9711 landed at Zhejiang Province, and then northward along the line of ZheJiang, AnHui, ShanDong. Before landfall, Jiangsu coasts is under the effects of east gale; after landfall Jiangsu coasts has been effected by southeast wind continuously, the basic wind speed is about 20m/s or so. And use the measured wind data of Jiangsu coastal weather stations during 9711 typhoon to verify wind field model computing results. The Calculated wind speed and direction values are in good agreement with the measured values, which laid the foundation for the next storm surge simulation. The Verify figures are not given in this paper.

2.2 2-Dimensional storm surge model for Jiangsu coastal model – ADCIRC

2.2.1 The governing equations

The control equations adopt hydrostatic assumption and Boussinesq approximation. In order to avoid numerical perturbation, continuity equation adopts generalized wave continuity equation：

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0 \tag{2}$$

Here ζ is water level, τ_0 is weight parameter, U and V is flow velocity, H is water depth, $\tilde{J}_x$ and $\tilde{J}_y$ are parameters that calculate from momentum equation.

ADCIRC solving differential equations discrete scheme in time, using the finite element space discretization scheme. In the semi-implicit scheme time differential equation using nonlinear terms in the display, the time-step mode longer receive Courant limit. Application of linear interpolation on unstructured triangular mesh and mesh vertices in each of three degrees of freedom is calculated solving the water level and flow rate, ζ U and V.

2.2.2 Model range, mesh and parameter selection

Figure 1 shows the trend of Jiangsu coastal grid computing model. Located near the northern boundary of the model Chengshan Shandong Peninsula, located near the southern border of Zhejiang Oujiang estuary, off the coast of the border with Jiangsu substantially parallel to the coastline, from the shore about 300km. The minimum mesh of the model is about 2'. There are 95125 grid cells and 49023 nodes in the mesh.

The time step 1s, horizontal diffusion coefficient of viscosity 10m^2 / s. Bottom friction coefficient determined as:

$$C_{db2d} = C_{f\min}\left[1+\left(\frac{H_{BREAK}}{H}\right)^{\theta_f}\right]^{\frac{\gamma_f}{\theta_f}} \tag{3}$$

Here, C_{db2d} is bottom friction coefficient, $C_{f\min}$ is the bottom friction coefficient in the smallest water depth, H_{BREAK} the controlled water depth, θ_f、γ_f are coefficients. It can consider different water depth to adapt the sand bar area.

2.2.3 Typical storm surges validation

Through analysing typhoon track data, there are 3 types of tropical cyclones which can have effects on this area: direct landing, northward after landing and only sea moving. Taking the damages caused by typhoon storm surge into consideration, 9711 "Winnie" Typhoon, 0012 "Prapiroon" Typhoon and 1210 "Damrey" respectively, as landing north, offshore activity type and front landing typical type (Fig. 2), were selected as typical examples to study the storm surge and flow field characteristics.

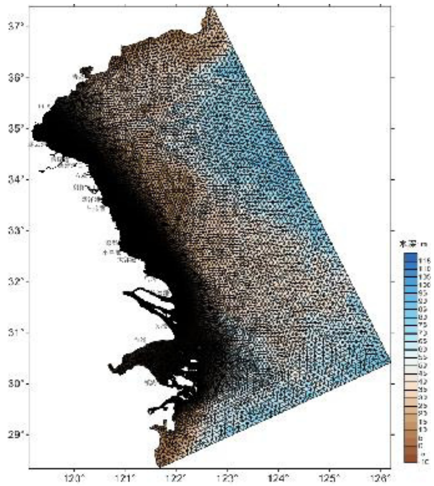


Fig. 1 The grid mesh for Jiangsu coastal and offshore

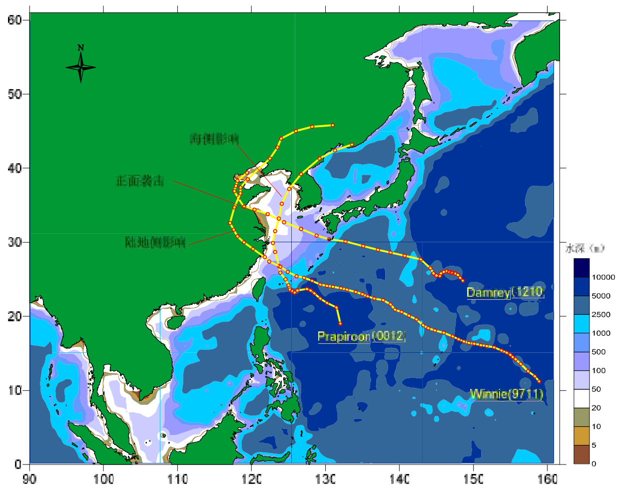
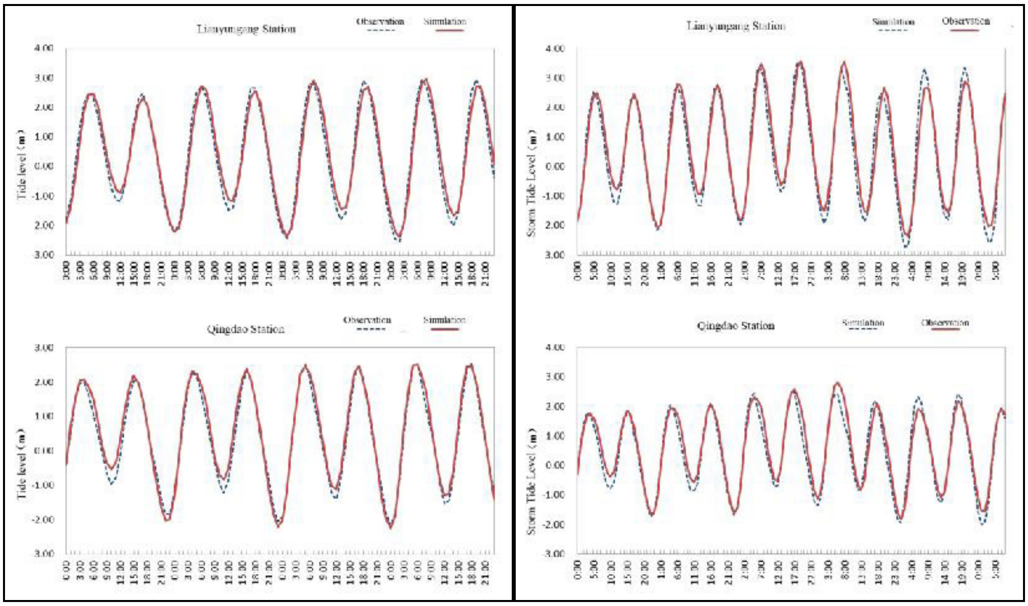


Fig. 2 The typical Typhon path affected Jiangsu coastal

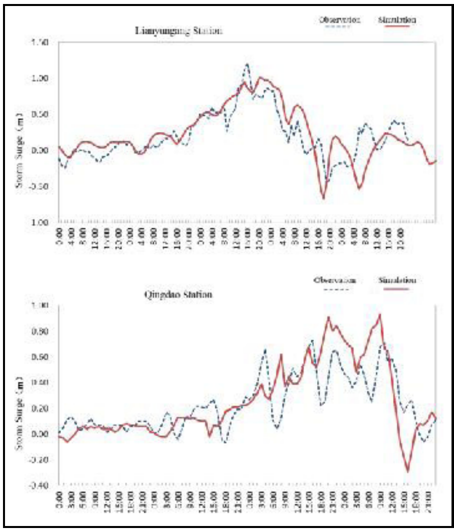
The 9711,0012 and 1210 three simulated storm surges, the simulation process of astronomical tide and storm surges are in good agreement with the observational results, the results shows that the use of the boundary conditions, the wind field data and model parameters are suitable for the radial submerged sand bars coastal area.

From storm surge process point of view, during the 9711 typhoon storm surge, the largest rise of water level is 1.20 and 0.80m respectively at Lianyung Gang and Qingdao station, belong to the "standard" storm surge(Fig.4), the water level surge have the before vibration, main vibration and back vibration occurence. The biggest surge at Lianyungang during the 0012 typhoon around 0.80m, the biggest increased water level at Lusi around 1.20m, the increasing water process presents certain "fluctuation" feature, reflecting the interaction of storm surges and tides, which is particularly evident at Lusi station(Fig.5). During the 1210 typhoon, the maximum surge at Lianyungang station close to 2.00m, the biggest increase in water at Lusi stations are more than 1.10m. The Lianyungang station showing a typical process by "Standard" surge, the main vibration is very prominent, the Lusi station surge showing "fluctuation" features.



a. Astronomical Tide b. Storm Tide

Fig. 3 Astronomical Tide and Storm Tide Verification during Typhoon No.9711



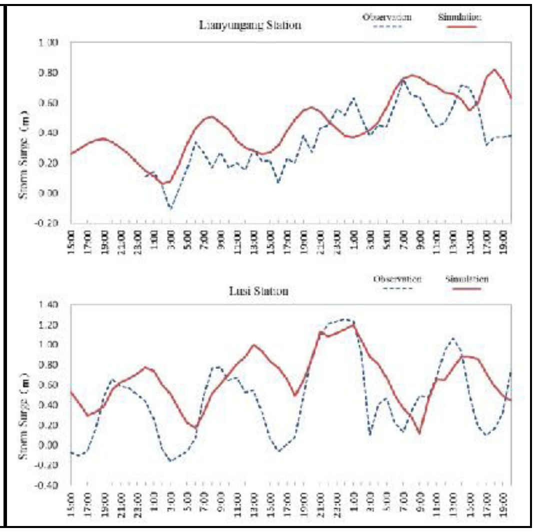


Fig. 4 Surge Curve of Typhoon No. 9711 Fig. 5 Surge Curve of Typhoon No. 0012

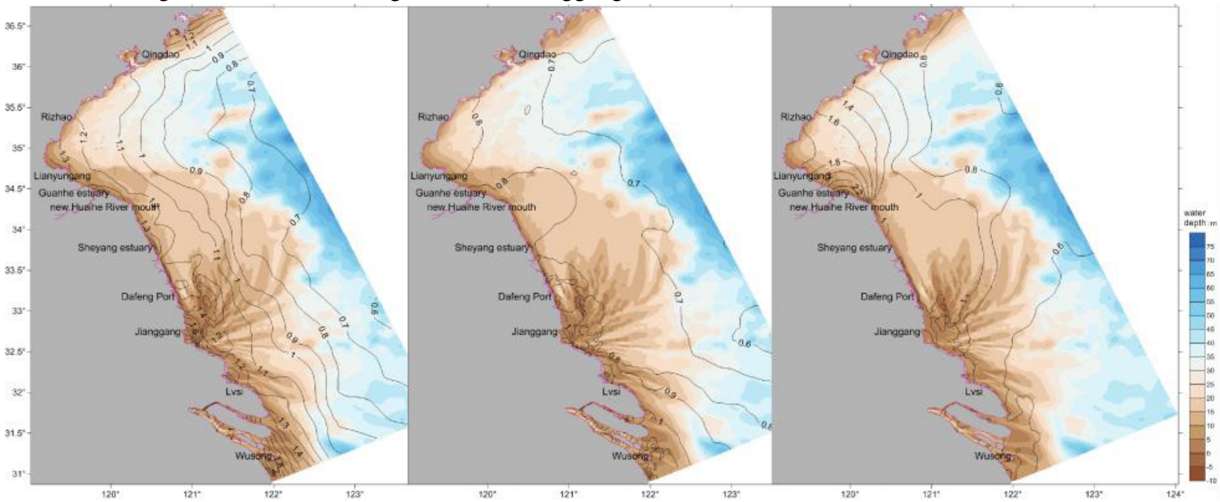
3. Storm surge characteristic in radial submerged sandbank area

3.1 9711 storm surge

From the simulated typhoon tide current field process for 9711(Wennie) approaching to coastal Jiangsu, Beijing at 08:00 on August 19, the typhoon center located in Zhejiang, Jiangsu coastal was in easterly winds along the coast, but this time the tide was in flooding process around Yangtze Delta including the submerged radial sandbars area, and the tidal flow and wind was in the same direction, Jianggang south tidal flow speed significantly strengthened the trend under coupled action of flooding current and wind , the flow direction deflect to northeast ;

Among Sheyang estuary to Jianggang coastal area, the tide flows direction turned to the west of the land. At 14:00 on the 19th, while at the center of the typhoon moved northwards, the wind in Jiangsu coastal turned to southeast. In this case, the submerged radial sandbank was at ebb tide. The ebb current was turned to northward (deflection to the left) significantly under the role of wind in the Waste Yellow River mouth, Jianggang and its south sea area. At 20:00 on the 19th, also effecting by southeast wind, the flooding flow further strengthened in south Jianggang sea area.

Figure 6a is the maximum calculated setup of water level in Jiangsu coastal water distribution during the 9711 typhoon, it can be seen that during the 9711 typhoon, the biggest increase in Jiangsu coastal water distribution presents small offshore, near-shore big; the distribution of contours near parallel to the coastline of Jiangsu. The maximum setup happening at open sea near Jiangsu is about 0.70m, and the setup near-shore over is 1.20m, of which the largest increase exceeding to 2.0m at Jianggang.



a. 9711 *b. 0012* *c. 1210*

Fig. 6 the maximum calculated setup of water level

3.2 0012storm surge

From simulated flow field distribution for 0012 Typhon moving through Jiangsu offsea can be seen when the center of the typhoon Close to the periphery of the Yangtze River Estuary, the coastal Jiangsu was in east wind effect. The ebb tidal flow was in status of anticlockwise circulation under the action of Typhoon rotating wind in counterclockwise offshore the Yangtze Delta. The ebb tidal flow in submerged radial sandbank turned to west (left) deflection. When the center of the typhoon arrived at offshore of the submerged radial sandbar, in south Jianggang, the westerly winds made the flood flow deflected to east (ie, left), and the water level decreased; in north Jianggang north-east winds made the flood flow to the west side to shore (right) and water level increased. When the typhoon center arrived at offshore of Lianyungang, the middle of Huanghai, the south sea of Dafeng Port winded by westerly winds, sea water was in decrease, the wind tend to ebb flow east. When the typhoon center position moved further north, the wind was in *w*esterly wind in coast of Jiangsu, and in the south east in the submerged radial sandbar area and little change of westerly wind in Haizhou Bay, the sea level had little changed.

Figure 6b is the largest setup of water level distribution in coastal Jiangsu during 0012 Typhon. it can be seen, the largest increase offshore is around 0.60-0.70m, the distribution of setup substantially parallel to the contour line of water depth; the water level increase significantly with approaching to shore, it also regulated by tide. The water level increase the most significantly are at Jianggang and Lusi, over 1.30.

3.3 1210storm surge

From simulated flow field distribution for 1210 Typhon moving through Jiangsu off sea can be seen when the center of the typhoon arrived at Lusi seas, Jiangsu seas was in role of north-east wind, flood tidal flow was southerly in the south of Jianggang seas. The flood flow turned to north-west. When the center of the typhoon reached to offshore of Dafeng, the flow in the center of Typhon was in counterclockwise circulation under the action of anticyclone. In the west of the center of the typhoon, the ebb flow at Dafeng Port obvious trend to the west side of the deflection (turn left), south of the typhoon center, radiation sandbar tide waters off the west, north to the deflection. In the south, the ebb flow in submerged seas deflected to west and northern. When the center of the typhoon reached to offshore of the wasted Yellow River mouth, the flow in the center of Typhon was in counterclockwise circulation, there was a clockwise direction circulation structure in the east Dafeng Port of the south of the center.

After landfall, Jiangsu coastal fundamental role in southeast wind, waste waters of the Yellow River mouth to Jianggang deflected off the trend is towards the west (turn left), Jianggang waters south of the north side of the ebb flow deflection (turn left).

Figure 6c is the largest setup of water level distribution in coastal Jiangsu during 1210 Typhon. The maximum surge obvious occurred at landing point Guanhe estuary east) as the center, gradually reducing from the center to outside. The largest setup of water was about 2.80m, the largest increase from new Huaihe River mouth Jianggang seas was 0.80-1.00m, The largest water level increase in south of Jiangsu coastal was about 0.60-0.80m.

4. Conclusion

This paper studied the storm surge characteristic for different type of typhoon around Jiangsu coastal seas, special for the submerged radial sandbar area and gave a discussion for the different typhoon about the surge distribution. The main conclusions are as follows:

It established a multiple coupled storm surge numerical model, which validates well and gives good explanation for simulation of storm surge in Jiangsu seas area.

The three kinds of storm surge can be representatives for all kinds of the storm surge in this area. 9711 "Winnie" Typhoon, 0012 "Prapiroon" Typhoon and 1210 "Damrey" are chosen respectively as landing north type, offshore activity type and direct landing type. For landing north type and offshore activity type, the distribution of setup contours is near parallel to the coastline; for direct landing type, maximum surge obviously occurs at landing point, and setup reduces gradually from the centre to outside.

In the submerged radial sandbars of the Southern Yellow Sea, storm surge distribution is complicated. It has a close relationship with sea-floor relief and the combination of passing time of typhoon and astronomic tide.

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